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Research article

Dam operations may improve aquatic habitat and offset negative effects of climate change

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Dam operation impacts on stream hydraulics and ecological processes are well documented, but their effect depends on geographical regions and varies spatially and temporally. Many studies have quantified their effects on aquatic ecosystem based mostly on flow hydraulics overlooking stream water temperature and climatic conditions. Here, we used an integrated modeling framework, an ecohydraulics virtual watershed, that links catchment hydrology, hydraulics, stream water temperature and aquatic habitat models to test the hypothesis that reservoir management may help to mitigate some impacts caused by climate change on downstream flows and temperature. To address this hypothesis we applied the model to analyze the impact of reservoir operation (regulated flows) on Bull Trout, a cold water obligate salmonid, habitat, against unregulated flows for dry, average, and wet climatic conditions in the South Fork Boise River (SFBR), Idaho, USA.

Our result showed that regulated and unregulated flows had similar aquatic habitat quality regardless of climatic conditions except for the summer period, when habitat quality was higher in the regulated than unregulated flow scenario due to lower stream temperature in the former than latter case, underpinning the importance of thermal regimes. Current dam operation provides a suitable habitat for Bull Trout year-round but blocks the migration corridor to a portion of the headwater tributaries. Conversely, unregulated flows had an unsuitable thermal regime during the warm summer period but fish were able to migrate to cooler headwater streams. Dam management maintained high quality habitat during a series of drought climatic years, thus we suggest dam management may be used to offset or mitigate impacts of future climatic variability and climate change on aquatic habitat.

1. Introduction

Dams are beneficial to fulfill food and energy demand as well as for recreation, flood control and environmental water management. However, their management affects hydrological processes, alters stream flow, sediment transport, water temperature, and potentially habitat loss and reduction of aquatic biodiversity (Bunn and Arthington, 2002; Poff et al., 1997; Ward and Tockner, 2001, Benjankar and Yager, 2012). Typically, regulated flow decreases magnitude of peak flows and increases minimum base flows. Dam management impacts stream thermal regimes spatially and temporally beside hydrological alterations (Angilletta et al., 2008; Preece and Jones, 2002; Steel and Lange, 2007). However, the magnitude of its effects depends on many factors such as size and purpose of the dam, magnitude of flow release from the dam and local hydraulics (Lessard and Hayes, 2003).

Not only human influences, but also gradually changing climate may increase precipitation variability and extreme events, e.g., droughts and floods (IPCC, 2013) and decreased snowpack, thereby

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altering stream hydrology and thermal regime (Dettinger and Anderson, 2015; Isaak et al., 2010; Sohrabi et al, 2013). Extreme climatic events are expected more frequently with global climate change (Diez et al., 2012). Furthermore, changing climate will impact the thermal regime of river systems as well as shift the availability of certain aquatic habitats selected by different species (see, Battin et al., 2007; Perry et al., 2005). However, reservoir management may mitigate or prevent some detrimental effects of climate change on the downstream aquatic habitats.

Following previous studies, which showed that reservoir management could provide an opportunity to manipulate water temperatures via flow release, to accommodate aquatic species requirements (Null et al., 2013; Yates et al., 2008), we test the hypothesis that dam management could help mitigate some of the impacts caused by climate change on stream flows and temperature downstream. We use a process-based integrated model, which couples catchment hydrology, hydraulics, water temperature and fish habitat models to quantify the impacts of dam operation on aquatic habitat quality for different climatic conditions and compare the habitat quality between regulated and unregulated (natural flow and thermal regime) flows.

To address our goal, we used the South Fork Boise River (SFBR) (Idaho, USA) as a study site, whose hydrology is regulated by Anderson Ranch Dam and reservoir operation. The reach is a critical rearing habitat for Bull Trout, which is classified as a threatened species and whose habitat is federally protected through the Endangered Species Act (ESA). We hypothesized that dam management changed fish habitat downstream in turn altering the behavior of Bull Trout and their use of the area. We evaluated reservoir-operation impacts on aquatic habitat under extreme climatic conditions such as droughts, which may persist for several years and floods.

2. Methods:

2.1. Study area

The South Fork Boise River (SFBR), located between Anderson Ranch and Arrowrock Reservoir is ~45 km long and, has average width of 41 m and slope of 0.0043 (Fig. 1). The basin hydrology (drainage area of 3382 km^2) is snowmelt dominated, with snowmelt runoff occurring from late March to May. The runoff periods are followed by warm, dry summers, which result in decreased stream flows. Stream flows are regulated by Anderson Ranch Dam for irrigation, flood control and power production. The regulated maximum flows occur in May during normal water years when the reservoir fills. The river can be divided into two segments a 23 km long (upper) south open canyon reach, which is site for this work, and a 22 km long (lower) north narrow canyon reach. The study reach has pools, riffles and runs with several braided sections and side channels. Most of the side channels are ephemeral, connected wilth the main channel during high flows, while some side channel are connected throughout the year.

2.2. Integrated model

We used an integrated modeling framework (Benjankar et al., In Preparation) that couples catchment hydrology and water temperature (Sohrabi, 2016; Sohrabi et al, 2017), hydraulics, water temperature and biological (fish habitat) models to analyze the impacts of dam operation on aquatic habitats. For hydrologic model to estimate the relationship between rainfall and run-off, we used Penn State Integrated Hydrology Model (PIHM), is a fully coupled and semi-distributed hydrologic model (Kumar et al., 2013). The model simulates hydrological processes, including evapotranspiration, surface and subsurface flow and stream flows from soil moisture of unsaturated zone and groundwater table. The hydrologic model was calibrated for water year 2010 at Featherville gage station and validated the model for 2006, 2007 and 2013 water years at Featherville and for 2006, 2007, 2010 and 2013 water years at Anderson Ranch Dam (Fig. 1). Percent BIAS (PBIAS) were less than 4% at both gage stations and for all years, except 2006 water year. Errors were 21% and 23% at Featherville and Anderson Ranch Dam gage stations, respectively for the year 2006 (Sohrabi, 2016).

We developed a one-dimensional (1D) and two-dimensional (2D) hydrodynamic model using DHI software MIKE 11 (1D) (DHI, 2011a) and MIKE 21 (2D) (DHI, 2011b) to simulate water temperature and hydraulics (flow depth and velocity). Hydraulic models are constrained with upstream (discharges) and downstream (water surface elevations) boundary conditions and 2 m by 2 m resolution digital elevation model (DEM) of both terrestrial and submerged topographies surveyed with the aquatic-terrestrial Experimental Advanced Airborne Research LiDAR (EAARL) (McKean et al., 2009). The 1D model was supported by high-resolution cross-sections extracted every 30 m from the DEM. Hydrograph and thermographs were recorded at the reservoir outlet and were used as boundary conditions for hydraulic and temperature models for the regulated case. For the unregulated case, we used the thermograph of the SFBR upstream of the reservoir.

The 1D hydraulic and temperature model extends the 45 km reach from Anderson Ranch Gage Station to the Neal Bridge Gage Station (Fig. 1). The model was calibrated by comparing simulated and measured water surface elevation (WSE) for discharges 8.5 and 45.6 m^3/s. Root mean square error (RMSE) for 8.5 and 45.6 m^3/s were 0.12 m at random locations. For model validation, we compared simulated and observed WSEs and water wave-travel at three locations: Cow Creek Bridge, Private Bridge and Canyon section (Fig. 1). The model predictions matched the patterns of water surface elevations at all three stations and RMSEs were 0.02–0.15 m. Comparisons between simulated and measured temperatures at Cow Creek Bridge, Danskin Bridge, Private Bridge and Canyon section showed RMSE of 0.70–1.43 °C, which are comparable with other studies (Hébert et al., 2015; Loinaz et al., 2013; Wang et al., 2010).

We developed a 2D hydraulic model for the entire study site (23 km) with a 2 m grid size DEMs (Fig. 1). The 2D model was calibrated by comparing observed and predicted WSEs (at several locations along the reach) and flow velocities (at 2 cross sections) measured at 8.5 m^3/s discharge. The model was validated with WSEs at discharges of 17 and 46 m^3/s, and with velocities measured along the reach at the discharge of 17 m^3/s because of safety concerns at higher flows. RMSEs for WSE were between 0.18 and 0.2 m, whereas velocity RMSEs ($R^2 = 0.77$) were between 0.07 and 0.25 m/s. The simulated flow wave matched the observed pattern fairly well, which strengthens our confidence in the developed model. The performances of both WSE and velocity for calibration and validation flows were comparable to those reported by other studies (e.g., Boavida et al., 2013; Guay et al., 2000; Pasternack et al., 2004; Tarbet and Hardy, 1996).

We developed a fish habitat model in ArcGIS using simulated hydraulic variables of water depth and velocity, water temperature and univariate rearing habitat preference criteria for Bull Trout (Fig. 2a). Water depths and velocities for rearing habitat preference curves were adopted from previous studies (Lewis River workshops, 2000; WDFD, 2004). Observed water depths and velocities at Bull Trout observed locations in the SFBR system fitted fairly well with the adopted univariate curves. Geometric product of the individual suitability indices, *SI*, of physical parameters of water depth and velocities were used to determine the habitat

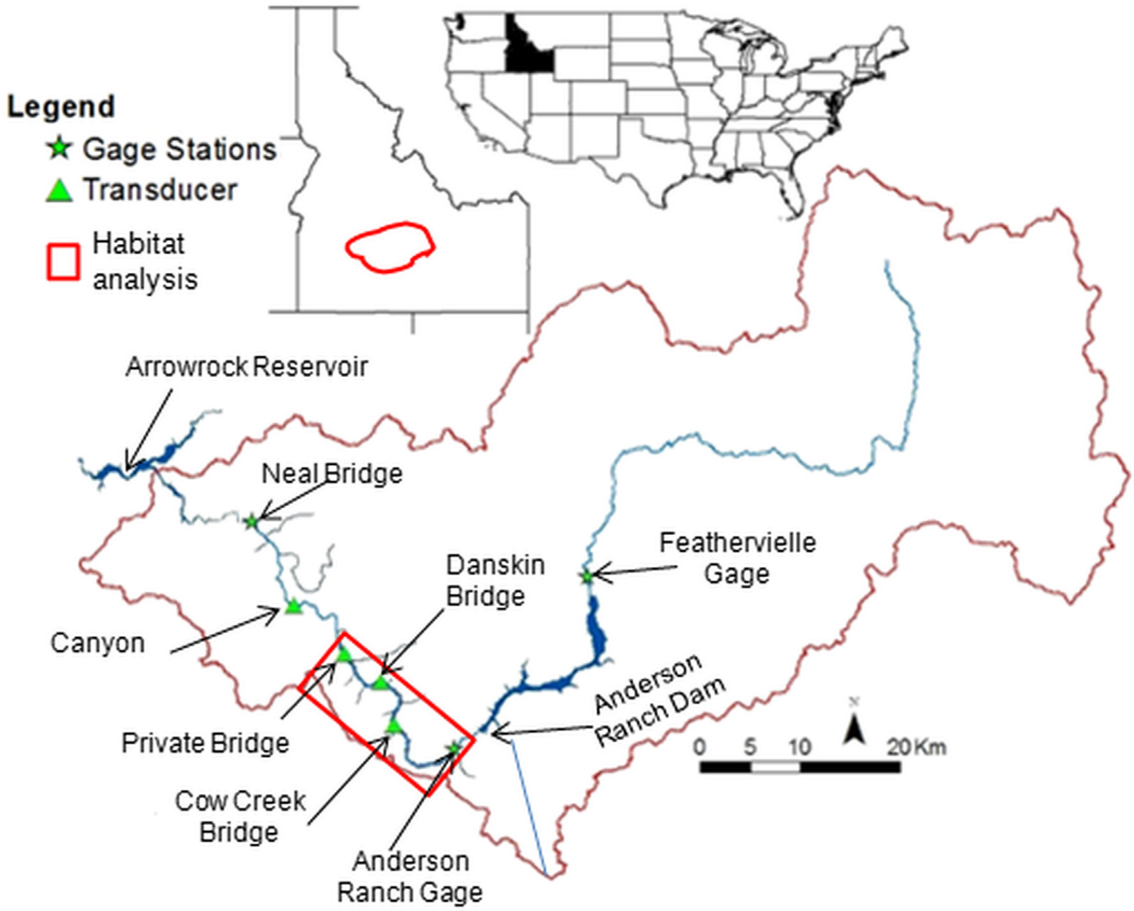

Fig. 1. Map of the study area.

suitability index (*HSI*) and weighted usable area (WUA) (Fig. 2b). Then, we developed relationships between discharge (simulated) and WUA and discharge (simulated) and HSI to have a function to describe a continuous change of habitat quality with discharge (Fig. 2b).

We used daily maximum temperature (DMT) as a metric for temperature suitability index (SI_t) for each day based on literature information. Previous researchers concluded DMT above a critical threshold is a fundamental parameter for determining distribution of the majority of aquatic species (Olden and Naiman, 2010). Based on literature review (Bonneau and Scarnecchia, 1996; Maret and Schultz, 2013; McMahon et al., 2007; Poole et al., 2001; Selong et al., 2001), we identified SI_t for <16 °C and >22 °C are 1 and 0, respectively, and SI_t decreases linearly between 16 and 22 °C. Furthermore, we verified water temperature preference curves by comparing stream water temperatures at Bull Trout locations in the South Fork Boise River. Because DMTs do not change considerably spatially (from upstream to downstream) for the specific day in our study site, we used a single SI_t for the entire study area (see, Maret et al., 2006).

We calculated suitability index for each *i*-th grid cell ($SI_{i,j}$) and *j*-th variable, considering water depth ($SI_{i,d}$),velocity ($SI_{i,v}$) and temperature ($SI_{i,t}$) and preference criteria for those variables using eq. (1), which simplifies to eq. (2) when SI_t is constant over the entire study area for the specific day, as in our case:

$$SI_{\mathrm{i}} = \sqrt[3]{SI_{i,d}{*}SI_{i,v}{*}SI_{i,t}} \tag{1}$$

$$SI_{\mathrm{i}} = \sqrt[3]{SI_t}{*}\sqrt[3]{SI_{i,d}{*}SI_{i,v}} \tag{2}$$

We developed habitat time series under dam regulated and unregulated scenarios based on Q-WUA and Q-HSI curves and measured mean daily discharges and temperatures (Fig. 3), which is an indicator for long-term impacts of dam operation on fish habitat. Habitat time series, which is an extension of the Instream Flow Incremental Methodology (IFIM) approach, can be used to indicate temporal status of habitat (Li et al., 2015; Muhlfeld et al., 2012). Fundamental behind habitat time series is that habitat is a function of stream flow and thus varies temporally. One of the advantages of this approach is that it allows for comparisons of flow management regimens. Mean daily discharges were used to interpolate daily WUA and HSI from the Q-WUA and Q-HSI curves, respectively. Then, we calculated daily WUA (d) using eq. (3) from interpolated hydraulic-quantified suitability index SI_h (product between SI_v and SI_d) and temperature (SI_t) suitability indices for the specific day, where (SI_t) and (SI_h) varies daily based on DMT and mean daily discharges, respectively. Furthermore, we calculated daily HSI (d) using eq. (4).

$$\mathrm{WUA(d)} = \sum_{\mathrm{i=1}}^{\mathrm{N}} \left(\prod_{\mathrm{j}}^{\mathrm{m}} \mathrm{SI_{i,j}} \right)^{1/\mathrm{m}} \mathrm{A_i} \tag{3}$$

with *N* is the total number of cells within the wetted area of the stream for a given discharge, *m* is number of variables, A is the area of a grid cell, which is constant for our model. The HSI,

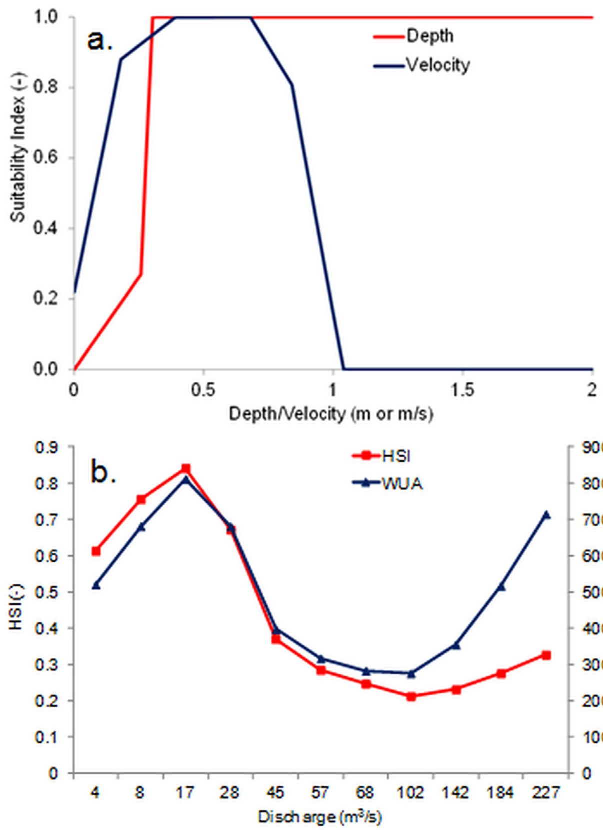

Fig. 2. a. Water depth and velocity preference curves for bull trout adult, b. Weighted usable area (WUA) and habitat suitability index (HSI) for different discharges.

dimensionless form of WUA is:

$$\mathrm{HSI(d)} = \frac{\mathrm{WUA(d)}}{\sum_{i=1}^{N} A_i} \tag{4}$$

2.3. Analysis

We selected three functional climatic conditions to represent typical wet, average and dry climatic years based on measured flows at USGS gage at the SF Boise River near Featherville, ID from 1946 to 2012, which is located at the upstream of the Anderson Ranch Reservoir. Frequency analysis was performed for the measured flows to estimate recurrence interval (RI) floods. Typical wet, average and dry years were identified based on annual natural flow characteristics of the basin. We selected dry (2007), average (2010) and wet (2006) years based on flow magnitude of less than 1.5-year RI, between 1.5 and 5-year RI and greater than 5-year RI, respectively in both annual maximum and mean floods and based on drought indices calculated for the region (Sohrabi et al., 2015).

To evaluate impacts of dam management on fish habitat, we compared WUA time series for three functional climatic conditions dry (2007), average (2010) and wet (2006) between dam regulated and unregulated scenarios. First, we compared WUA calculated by water depth, velocity and stream temperature (hereafter habitat) and WUA only based on hydraulic variables water depth and velocity (hereafter hydraulic-quantified habitat) between regulated and unregulated scenarios. For the hydraulic-quantified habitat, we assigned water temperature suitability index (SI_t) as 1 for each day assuming water temperature suitability is optimal (eq. (3)).

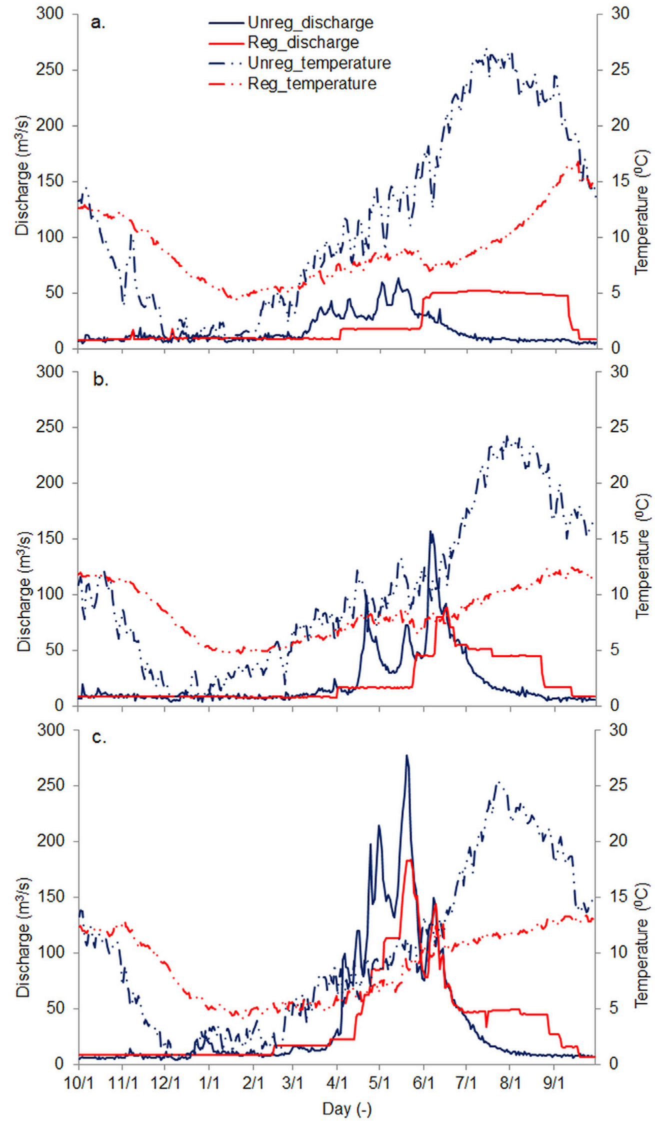

Fig. 3. Regulated and unregulated discharge and daily averaged water temperature measured at the Anderson Dam outlet for a. dry (2007), b. average (2010), and c. wet (2006) climatic years.

Comparisons between habitat and hydraulic-quantified habitats evaluate impacts of water temperature on aquatic habitats. Previous study and water temperature measurements show unregulated temperatures are noticeably higher than regulated temperatures in the SFBR system, thus we contemplated that this may have negative impact on Bull Trout habitat (USBR, 2013). We also compared HSI duration between regulated and unregulated scenarios for 18 years period (1999–2016) in order to quantify impacts of climatic variability on aquatic habitat.

3. Results and discussions

Anderson Ranch Dam has altered hydrology and thermal regimes, causing minimum base-flow to increase and peak-flow to decrease distinctly (Fig. 3). Unregulated flow hydrographs of SFBR system peak from late March to May with cold waters as a result of snowmelt and have warm low flows in the dry summer period. Comparatively, regulated flow hydrographs have increased winter water temperatures and decreased summer water temperatures.

Anderson Ranch Dam management has smoothened the peak of hydrograph by storing water for later use (e.g., energy production and irrigation) and flood management downstream, which has resulted in relatively higher and stable flow during summer, fall and winter months similar to other regulated systems (e.g., Muhlfeld et al., 2012; Yarnell et al., 2010).

3.1. Dam impact

Habitat time series analyses showed habitats were consistent in late-fall (October and November), winter (December, January and February) and early-spring months (March) as a result of steady regulated higher low-flows and colder stream temperature less than 16 °C, which benefits Bull Trout rearing habitat downstream of Anderson Ranch Dam (Figs. 3 and 4). Habitat increased during later stages of spring months due to medium low-flows (higher than the winter) release from the dam. Habitat increments by medium low-flows were more noticeable for wet than for dry and average climatic conditions for the late-spring months (Fig. 4). Later, habitat decreased in summer and early-fall months as a result of high flow release to fulfill irrigation demand downstream. Patterns of habitats for the unregulated scenario were similar to the regulated in fall and winter months for all dry, average and wet climatic conditions (Fig. 4). Habitat distributions were consistent throughout all climatic years dry, average and wet for the regulated scenario.

Habitats were noticeably higher quality for wet than dry and average conditions for spring months. Their quality decreased considerably in summer months for the unregulated scenario but not for the regulated scenario. For flows higher than bankfull (68 m^3/s), mostly during summer months, river (main channel) velocities were generally higher than 1 m/s in the SFBR system for both regulated and unregulated scenarios, which reduced habitat drastically because the flow velocity (more than 1 m/s) is unsuitable for Bull trout (Fig. 2a and b). Habitat qualities were comparable for both regulated and unregulated scenarios during fall, winter and spring months but habitat had higher quality for the regulated than unregulated flows during warm summer months regardless of climatic conditions. The poor summer habitat quality for the unregulated case is due to unsuitable warm stream water temperatures and higher summer discharges (Figs. 3 and 4). Other studies have also shown that smoothing flow is beneficial to river ecosystem maintaining suitable habitat for native fish and invertebrate communities (e.g., Muhlfeld et al., 2012).

The temperature effect on habitat quality remained consistent in all three climatic conditions for the regulated scenario, because the large water pool in the reservoir maintains stream water temperatures less than 16 °C regardless of climatic conditions (Figs. 3 and 4). Hydraulic-quantified habitat qualities, quantified using velocity and depth, supposing temperature is not a limiting factor, were much greater than habitat quality considering temperature in summer months for the unregulated scenario and its value was comparable to the regulated scenario. This highlights the importance of temperatures as a key component of fish habitat and water quality.

Habitat duration curve analyses revealed that HSI for unregulated scenarios were high (0.8–0.9) and comparable to unregulated for 50% of year and then it decreased to 0 for up to 25% of year. The curve patterns were similar for all periods (1999–2016), except for extreme drought years (e.g., 2002 and 2013) (Figs. 5 and 6). Regulated flows maximize habitat quality (HSI) longer than unregulated flows (Fig. 5). Overall, regulated flow maintained HSI higher than 0.8 for 95% of year for most of studied period (1999–2016). HSI decreased to 0.4 for remaining period, but never decreased to 0 as for unregulated scenarios. Regulated flows maintained high (0.8) HSI for 85% of year for extreme drought years 2001and 2013.

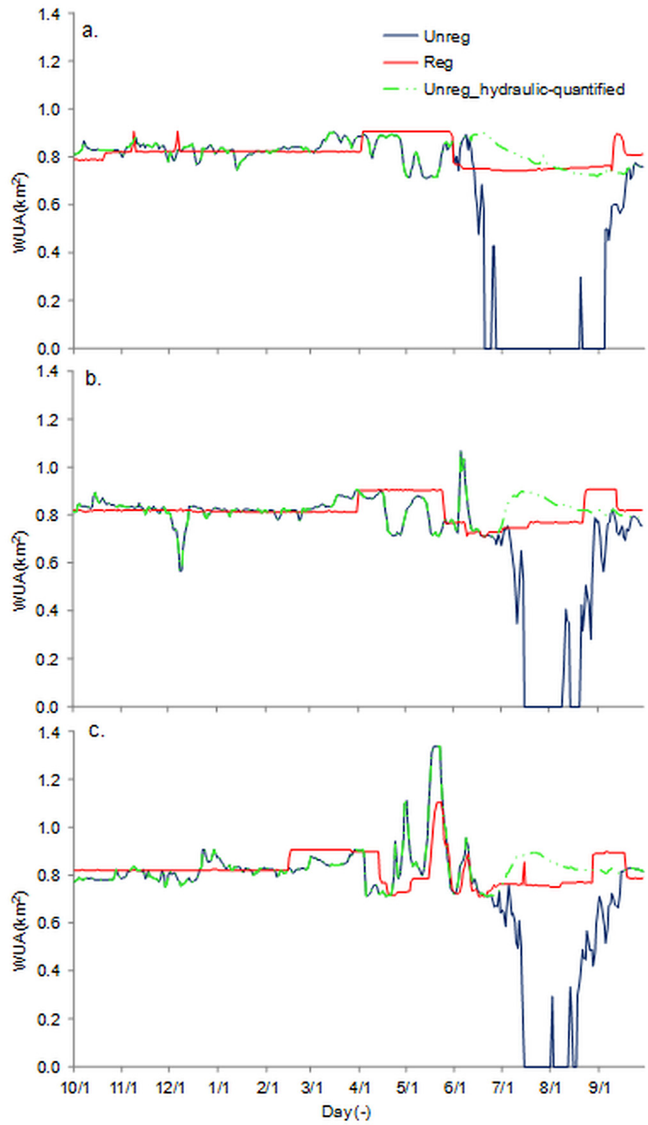

Fig. 4. Weighted usable area, WUA, with all three hydraulic variables water depth, velocity and temperature for regulated and unregulated flows for a. dry (2007), b. average (2010), and c. wet (2006) climatic years. Hydraulic-quantified WUA is based on water depth and velocity only.

Furthermore, our result showed that dam management maintained habitat quality even during multi-year drought periods, for example 2000–2004 and 2012–2016 (Fig. 6).

One of the main reasons for low HSI for the unregulated scenarios is water temperature above 16 °C (Figs. 3–5), which reduced Bull Trout habitat (USBR, 2013). Large late spring and early summer flows during the unregulated case also contributed to reduction in habitat. Furthermore, our results showed a similar pattern of HSI distributions for the regulated scenarios, except for years 1999 and 2012, where HSI was higher than 0.8 only for about 70% of year. Another study found that an increase in regulated flows below Hungry Horse dam have resulted reduction of Bull Trout habitat in the Upper Flathead River (Muhlfeld et al., 2012).

Our analysis showed that there is a good correlations ($R^2 > 0.5$) between reservoir elevation and dam released daily average and maximum temperatures (Figs. 6 and 7). Drought influenced reservoir elevation, which then may affect water temperature released from the reservoir (Fig. 6). However, even during historic droughts

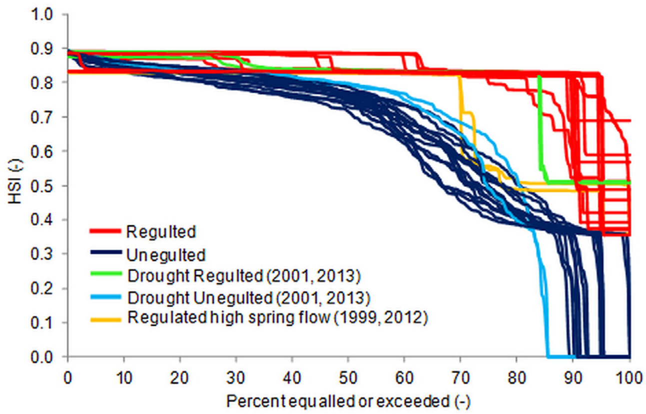

Fig. 5. Habitat duration curves for regulated and unregulated flows for years 1999–2016.

lasting several years the range of water temperature released from the dam was between 4 and 15 °C, still within the suitable conditions for Bull Trout. Difference between daily average and maximum water temperatures for the regulated cases were considerably narrow compared to unregulated cases (Fig. 7). These results are consistent with other studies where authors concluded drought reduces water volume but unaltered water temperature in deep and large reservoir (e.g., Dettinger and Anderson, 2015; Olds et al., 2011).

Our result underlines the importance of stream temperature as a critical variable for aquatic habitat (Anglin et al., 2004; Hillman and Essig, 1998; Poole et al., 2001; Selong et al., 2001). The Anderson Ranch Dam releases colder water, less than 16 °C and of minimum low flows higher than unregulated minimum low flows, which are exacerbated during drought year, are favorable to Bull Trout (Connor et al., 2003; Null et al., 2013). Bull Trout use the South Fork Boise River downstream year-round as both overwintering and summer rearing habitat during post-dam era (Salow and Hostettler, 2004). Historically, there were no migration barriers (e.g., Arrowrock and Anderson Ranch dams) in the SFBR systems, therefore Bull Trout could freely move toward headstream tributary habitats to avoid unfavorable water temperatures in the main stem river. Water temperatures in the unregulated scenario for the SFBR system are much higher (>22 °C) than the current regulated water temperatures (USBR, 2013) and late summer flows are considerably lower, therefore we speculate that without the dam, there would be very little favorable Bull Trout habitat during summer months (Figs. 3 and 4). Our data suggested that Anderson Ranch Dam management has not deteriorated Bull Trout rearing habitat downstream. Our results are consistent with other studies that dam management alters physical characteristics and water quality (temperature), however they were within a favorable range for Bull Trout resulting in better habitat in a regulated scenario than unregulated (see, Muhlfeld et al., 2012; Poff et al., 1997).

3.2. *Can dam management offset potential negative impacts of future climatic variability on aquatic habitat?*

Our results showed that water temperatures are higher than 16 °C for the majority of summer days in the unregulated scenario, consequently decreasing habitat quality (Figs. 3–5). Conversely, regulated-flow stream water temperature is within the range suitable for Bull Trout rearing habitat. This contributed to maximize the habitat and maintain the quantity and quality for the summer months. Hydraulic-quantified habitat qualities were much greater than combined (hydraulic and temperature) habitat quality. This underscores the importance of considering water temperature in modeling and predicting habitat quality.

Warmer water temperature may become a major issue in future

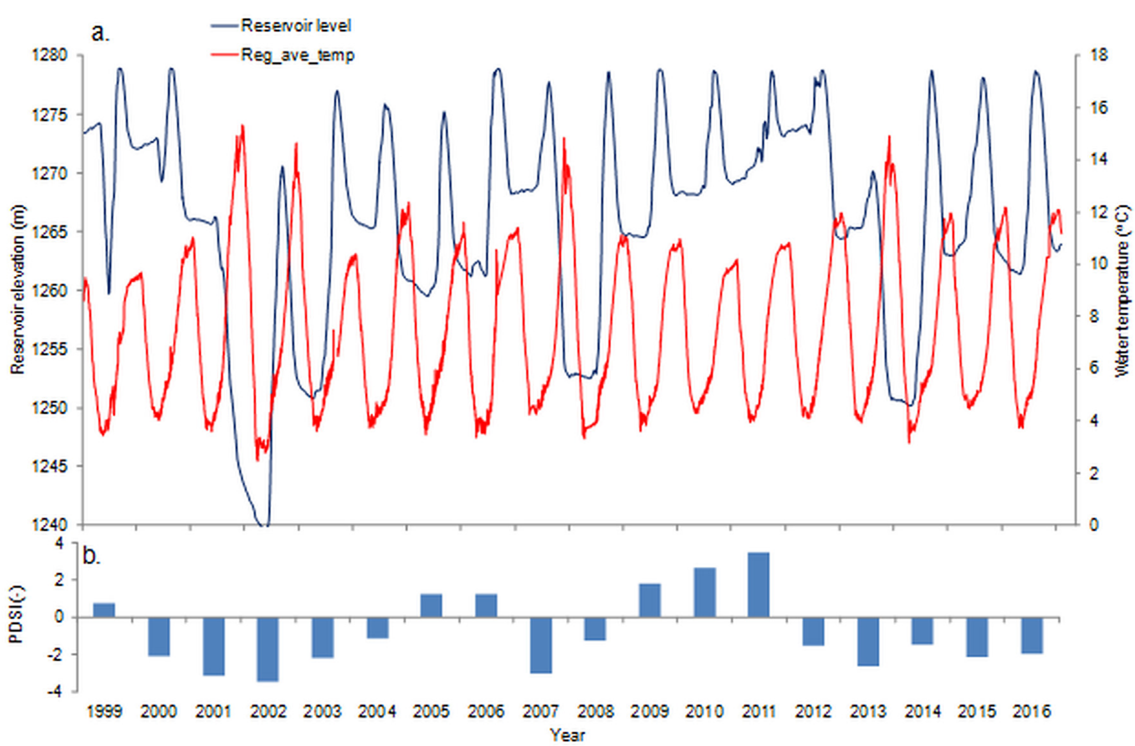

Fig. 6. a. Measured reservoir elevation and regulated (daily average) water temperatures climatic conditions for years 1999–2016. b. Climatic condition based on PDSI (Palmer drought severity index) for Elmore County, Idaho (Abatzoglou et al., 2014). Negative PDSI is an indicative of drought climatic condition.

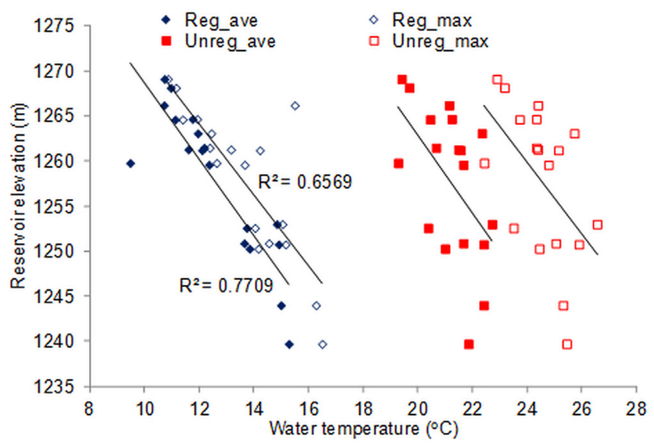

Fig. 7. Relationship between maximum yearly reservoir elevation and regulated and unregulated yearly average and yearly maximum water temperatures.

climates for aquatic habitat due to climate warming (Null et al., 2013). In our study, dam management reduced water temperature (less than 16 °C) for summer months and increased the minimum low flows (>8 m^3/s) in winter and spring months. This improved habitat quality from the unregulated scenario in all climatic conditions. Attention should focus on managing water temperature to maintain and enhance aquatic ecosystems in the future. Our study showed that dam management can offset the impacts of low flows and high water temperature on aquatic habitat by increasing natural low flows and decreasing water temperature. We found that dam management maintained high quality habitat for the entire year even during multi-year drought periods (e.g., 2000–2004 and 2012–2016).

We showed that dam management is able to maintain water temperature less than 16 °C, which is preferred by cold water species (e.g., Bull Trout) even during extreme drought years (e.g., 2002), when reservoir elevation is lowest within the period from 1999 to 2016. Furthermore, it reduced diel temperature fluctuation, which may have a negative impact on aquatic habitat. Based on our results, we argue that dam management may mitigate climate variability impacts on stream water temperatures to some extent, consequently on aquatic ecosystem as previous studies suggested (see, Null et al., 2013; Yates et al., 2008). Reservoir operations may provide suitable coldwater habitat for fish and wildlife by releasing hypolimnetic water from the bottom of the reservoir when high stream water temperatures are an issue. Nonetheless, the temperature of water releases depends on reservoir water temperature distribution, which is a function of reservoir water level, reservoir bathymetry, hydrodynamics and heat exchange. Therefore, research should include a reservoir model, such as Estuary, Lake and Coastal Ocean Model (ELCOM), to predict water temperature releases through dam based on carry-over volume of water from previous year, reservoir level, atmospheric temperature and climatic condition (Vilhena et al., 2010; Tranmer et al., 2018).

3.3. Study application

Magnitude of stream flow necessary to support aquatic ecosystems is an ongoing discussion of river restoration science and it may vary with different systems (Richter et al., 1997). Process-based integrated modeling can provide quantitative analysis to understand how regulated flows alter physical and thermal aquatic habitat conditions and riparian ecosystems (e.g., Benjankar et al, 2012). Our study underscores the importance of interdisciplinary studies that use a field and modeling approach, integrating physical process with biological responses to advance river science specifically for regulated systems (Murchie et al., 2008; Tranmer et al., 2018). This integrated modeling aid to understand the distribution of aquatic habitat quality as a function of flow and stream water temperature at the meter scale, which is key information for evaluating potential restoration alternatives over the catchment scale (Merenlender and Matella, 2013; Null et al., 2010; Yates et al., 2008). This analysis is possible because of the availability of new topobathymetric systems, like the EAARL, which provide detailed topography to support multi-dimensional hydrodynamic modeling to delineate and identify aquatic habitat distribution (Carnie *et al.*, 2015; Kammel *et al.*, 2016). These predictions can then be validated with field observation. Our study provides quantitative tools for river restoration decisions, which may go beyond expert knowledge or empirical relationship. However, these quantitative tools (hydraulic and habitat model) should be validated with site specific numerical data, like this work did, otherwise they may not serve future restoration objectives (Acreman and Dunbar, 2004).

4. Conclusions

Our results showed that regulated flows maximize the quantity of high-quality habitat as well as maintaining good habitat throughout the year for adult Bull Trout in the SFBR system regardless of climatic conditions. Summer months are a critical period for fish habitat in the SFBR system for unregulated flows in all climatic conditions, because summer stream water temperatures were comparatively higher than those suitable for Bull Trout. Water temperature caused poor to unsuitable habitats in summer and early fall months for the unregulated scenario. The negative impact of the stream thermal regime on habitat quality was further exacerbated by low river flows. In contrast, regulated flows maintain uniform good habitat throughout the summer period regardless of climatic conditions, because the Anderson Ranch Dam operations release stream water with temperatures within the range suitable for Bull Trout. Dam management maintains high quality habitat during extreme wet and dry climatic years and even with drought lasting several consecutive years. This supports our hypothesis that reservoirs have the potential to offset negative impacts on fish habitat from future climatic variability due to climate change.

We show that the advent of topobathymetric LiDAR coupled with advances in numerical modeling of both physical processes and habitat quality have provided new tools to develop "virtual watersheds", where we can simulate scenarios to test the impact of both human activities and natural events on ecosystems. These tools will allow us to design better, environmental friendly and sustainable infrastructures.

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